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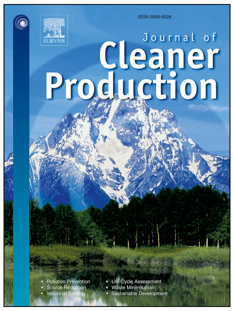
DOI:
10.1016/j.jclepro.2015.10.064

Accepted Manuscript



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PII: S0959-6526(15)01535-8

DOI: 10.1016/j.jclepro.2015.10.064

Reference: JCLP 6295

To appear in: *Journal of Cleaner Production*

Received Date: 8 October 2014

Revised Date: 14 September 2015

Accepted Date: 17 October 2015

Please cite this article as: Silva RV, de Brito J, Dhir RK, Establishing A Relationship Between Modulus Of Elasticity And Compressive Strength Of Recycled Aggregate Concrete, *Journal of Cleaner Production* (2015), doi: 10.1016/j.jclepro.2015.10.064.

ESTABLISHING A RELATIONSHIP BETWEEN MODULUS OF ELASTICITY AND COMPRESSIVE STRENGTH OF RECYCLED AGGREGATE CONCRETE

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Abstract: This paper provides a systematic literature review, based on the identification, appraisal, selection and synthesis of the evidence of 121 publications published over a period of 43 years from 1973 to 2015, relating to the effect of incorporating recycled aggregates, sourced from processed construction and demolition waste, on the modulus of elasticity of concrete. It identifies various influencing aspects related to the use of recycled aggregates such as replacement level, size and origin, as well as mixing procedures, exposure of the resulting concrete to different environmental conditions, use of chemical admixtures and additions, and development of the modulus of elasticity over time. A statistical analysis on the collated data is also presented with the purpose of understanding the loss of modulus of elasticity, based on quality and replacement level of recycled aggregates. Furthermore, a relationship between modulus of elasticity and compressive strength, in accordance with existing specifications for conventional structural concrete, is also proposed.

Keywords: Recycled aggregates, construction and demolition waste, concrete, modulus of elasticity, prediction model.

1 Introduction

Over the last 100 years, the exponential growth of the human population has led to a great expansion of the construction industry. It embodies one of the largest and most active sectors in the World, consuming more raw matter and energy than any other economic activity. Consequently, wastes produced by its activities comprise a major part of the overall amount of generated waste.

The increasing and unsustainable consumption of natural resources, as well as the excessive production of construction and demolition waste (CDW), has been a cause of great concern for the environment and economy. In order to reverse this trend, there have been several efforts to promote the ecological efficiency in the construction industry, one of them being the reutilization of CDW in new construction. By doing so, besides decreasing the amount of waste mass sent to landfills and the extraction of natural resources, more value will also be added to these materials, thus opening new market opportunities (Coelho and de Brito, 2013a, b). Indeed, the results of a life cycle assessment performed by Blengini and Garbarino (2010) gave encouraging results in terms of resources and from an environmental point of view, in that recycled aggregates (RA) play a key role in the sustainable supply mix of aggregates for the construction industry.

The global market for construction aggregates was expected to increase 5.2%/y until the current year of 2015, up to 48.3 billion t (Freedonia, 2012). In the USA, the Environmental Protection Agency (EPA, 2014) estimated that the generation of debris, from construction, demolition, and renovation of residential and non-residential buildings in 2003, was close to 170 Mt. According to Eurostat (2015), the total amount of waste generated in the European Union, in 2012, was over 2.5 billion t, 34% of which belonged to construction and demolition activities.

Bearing this in mind, the use of RA as replacement for natural aggregates (NA) in the production of concrete has been considered one of the most efficient methods for recycling certain materials from CDW and thus contributing to greater sustainability in construction.

Research on this subject started with basic observations on the effects of using recycled concrete aggregates (RCA) on the compressive strength of concrete (Buck, 1973; Frondistou-Yannas, 1977), as well as its economic feasibility (Frondistou-Yannas and Itoh, 1977). Since then, research on recycled aggregate concrete (RAC) has become progressively complex, introducing several new variables, in which the durability-related performance has also been considered. These more recent studies have generally shown a decline of the mechanical and durability-related performance, when compared to that of natural aggregate concrete (NAC), with similar characteristics (mix design, curing conditions, strength class, etc.).

The scope of this investigation was to bring together, analyse and evaluate the published information on the effect of RA on the modulus of elasticity of concrete. This property was chosen because of its importance in designing structures for the serviceability limit state, in which the main focus is the control of crack widths and the limitation of deflections. Contrary to compressive strength of RAC, which can be easily offset using a number of methods, investigation concerning the modulus of elasticity suggests that it generally strongly decreases with increasing RA content. This means that, even when the compressive strength of RAC is equivalent to that of a conventional concrete, its modulus of elasticity is generally lower, and therefore the deformations are higher, which is a source of distrust and an effective barrier to using RA in concrete, thus preventing the positive environmental impacts of reducing dumped materials and at the same soil dilapidation in stone quarries. A comprehensive statistical analysis on the relationship between the modulus of elasticity and compressive strength of RAC was also made, in order to establish accurate correction factors that can be easily applied by professionals in the construction industry.

2 Methodology

A very specific strategy was followed in the preparation of the systematic literature review provided in this paper. First, an initial list of publications was collected, based on various factors: relevance of the title in relation to the theme; aggregate type and aggregate size; and accessible data for statistical analysis.

Considering the vast number of publications, it became apparent that a full analysis of each publication would become an overly time-consuming process. Therefore, an initial appraisal became necessary in order to establish which of the publications were worth pursuing, based on the quality of their information.

For each publication collected, an expedient analysis was made in order to establish the relevance of its contents to the investigation, as well as the tests performed, main results and conclusions. This information was then properly identified and transcribed into a spreadsheet, containing various topics of interest for all publications.

As each publication was individually assessed, the relevant data regarding the production of recycled concrete (i.e. aggregates used, mix design, curing conditions, compressive strength and modulus of elasticity at various ages, etc.) were also collected. This information was then submitted to a statistical analysis in order to establish a relationship between the modulus of elasticity and compressive strength of RAC.

Afterwards, an initial table of contents was proposed to serve as a guide for the following investigation. This allowed a comprehensive exploration of the existing information on several factors relating to the use of RA in the modulus of elasticity of concrete.

When writing this paper, the key points were revealed from the analysis, evaluation and repackaging of data. This allowed drawing several conclusions on the effects of using RA on the modulus of elasticity, as well as the proposal of a simple approach to predict the performance of RAC, and thus facilitate its use in construction applications.

3 Recycled aggregates from construction and demolition wastes suitable for the production of structural concrete

According to existing specifications (BRE, 1998; BS-8500, 2006; DAfStb, 1998; DIN-4226, 2002; EHE-08, 2010; LNEC-E471, 2006; NBR-15.116, 2005; OT-70085, 2006; PTV-406, 2003; RILEM, 1994; TFSCCS, 2004; WBTC-No.12, 2002), there are three main types of materials arising from CDW, which, after being subjected to proper beneficiation processes in certified recycling plants, are suitable for the production of structural concrete; these materials are crushed concrete, crushed masonry, and mixed demolition debris. The composition of these materials may be found in Table 1.

4 Influencing factors on the modulus of elasticity of recycled aggregate concrete

The modulus of elasticity of concrete is known to be influenced by the cement paste, the aggregate's nature, the interfacial transition zone (ITZ) and the compacity of concrete (Neville, 1995). Like other properties, the modulus of elasticity also depends on the age of concrete, as a result of the cement paste stiffening over time.

The literature review has shown that there are countless ways of designing and producing concrete using RA. It was the authors' aim to identify and appraise the main issues related to the use of RA, which may affect the modulus of elasticity of concrete. These factors were: the replacement level of RA; the aggregates' size and quality; mixing procedure; curing conditions; chemical admixtures and additions content; and age of concrete.

4.1 Recycled aggregate replacement level

The collected literature unanimously suggests that there is a decrease in the modulus of elasticity as the replacement level increases, provided that every other parameter related to the mix design is constant. This loss is directly associated with the lower elastic modulus of RA, which consequently governs the modulus of elasticity of the resulting concrete.

The use of up to 30% of RCA has been considered to have minimal effects on the modulus of elasticity (Dhir et al., 1999; Dhir and Paine, 2004; Limbachiya et al., 1998). However, when 100% coarse RCA are used in the production of RAC, the modulus of elasticity may fall by as much as 20% to 40% (Frondistou-Yannas, 1977; Hansen and Boegh, 1985; TFSCCS, 2004; Xiao et al., 2005).

The effect of using 20% coarse RA, with varying RMA and RCA content, was studied by Dhir and Paine (2007). It was found that a RA blend composed of only RCA caused minimal effects on the modulus of elasticity (Figure 1a). However, as the RMA content increased in the MRA blend, the modulus of elasticity decreased. This effect was noticed by Gomes and de Brito (2007; 2009), who have also studied the effects of using increasing amount of MRA, with varying RCA and RMA contents, on the performance of concrete. Figure 1b shows that for the same replacement level, there is a greater loss in the modulus of elasticity as the RMA content increases.

The decline in the modulus of elasticity is heightened by the increasing amount of contaminants, such as plastic, rubber, soil, wood, which are lightweight constituents, and also bituminous materials. Studies on the effect of using plastic (Ferreira et al., 2012; Silva et al., 2013) and rubber (Bravo and de Brito, 2012; Valadares et al., 2012) on the properties of concrete showed clear losses in the compressive strength and modulus of elasticity and also resulted in decreasing performance in durability-related properties. It is possible to minimize these materials in processed CDW using wet separating techniques, which are effective to remove lightweight contaminants (Rodrigues et al., 2013). Research carried out on the introduction of increasing contents of asphalt-based aggregates (or reclaimed asphalt pavement - RAP) showed worrying losses in the compressive strength and moduli of elasticity (Huang et al., 2006; Huang et al., 2005). The use of 100% coarse RAP led to an almost 80% decrease in the modulus of elasticity. This can be explained by the existence of an impervious bitumen film in the ITZ between the RAP and the cement paste, thus preventing an effective bond between them. This reduction can also be explained by the less stiff asphalt film around the RAP, in comparison to the concrete matrix and NA. Therefore, a strong bond cannot be established between inorganic phases (cement and aggregate) and organic phase (asphalt) in concrete containing RAP. However, research on the influence of using RA from crushed glass (Serpa et al., 2015; de Castro and de Brito, 2013), which is often considered as a contaminant, showed that replacing a small amount of NA with these materials may lead to similar and even slightly higher moduli of elasticity when compared to that of the NAC.

Derived from the results of 476 concrete mixes, made with RA of different size, type and origin, sourced from 35 publications, Figure 2 shows the relative moduli of elasticity of concrete with varying RA content. This figure shows that the minimum relative modulus of elasticity for RAC with 100% coarse RA content was around 40% lower than that of the corresponding control concrete, which is in agreement with other findings (TFSCCS, 2004). An analysis of the upper and lower limits of the 95% confidence interval shows that there is a probability of 95% that RAC with 100% coarse RA content may exhibit moduli of elasticity between 0.97 and 0.52 times that of the control NAC.

The scatter of the results plotted in Figure 2 is the outcome of the combined effect of the large number of variables involved with the RAC, as previously stated. Contrary to what would generally be expected, it can also be seen from Figure 2 that some RAC results are higher than those of NAC. Generally, this comes as a result of using RCA sourced from concrete with greater strength and stiffness in the production of concrete with lower mix design strength.

4.2 Recycled aggregate size

The type of crushing devices used to break down larger pieces and the number of processing stages influence the size and shape of the resulting aggregates. The recycling process normally uses primary and secondary crushing stages. Jaw crushers, which are typically used in the primary crushing stage, provide the best grain-size distribution of RA for concrete production. A second crushing usually leads to rounder and less angular particles. It was found that it reasonably easy to produce good quality coarse aggregates that meet the size specification range by simply adjusting the setting of the crusher aperture (Hansen, 1992). However, it was found that during the production of fine RA, these tend to become coarser and more angular than any of the standard sands used in the production of concrete (Lamond et al., 2002) due to the existence of hardened cement mortar particles.

Studies (Corinaldesi, 2010; Debieb and Kenai, 2008; Huang et al., 2006; Kenai et al., 2002; Teranishi et al., 1998) have shown that fine RA tend to cause a higher fall in the modulus of elasticity than the coarse fraction. This effect is intensified when both coarse and fine fractions are used (Chen et al., 2003b; Debieb and Kenai, 2008; Maruyama et al., 2004; Teranishi et al., 1998; Yanagi et al., 1998).

Gerardu and Hendriks (1985) found that, while the use of coarse RCA caused a maximum loss of 15% in the modulus of elasticity of concrete, a 40% reduction was found in the same property when replacing sand by fine RCA.

Debieb and Kenai (2008) studied the effect of using coarse, fine and both fine and coarse RMA, obtained from crushing bricks, on the properties of concrete. The authors observed a reduction of up to 30, 40 and 50% of the modulus of elasticity, when the coarse, fine and both coarse and fine fractions, respectively, were used as full replacement of the corresponding NA size fractions.

However, it was found (Evangelista and de Brito, 2007; Yang et al., 2008) that it is possible for RAC mixes produced with fine RCA to present similar decreases in the elastic moduli as mixes made with coarse RCA. In one of these studies (Evangelista and de Brito, 2007), the authors observed that, when using 30% fine RCA to replace sand, minimal effects were noticed on the modulus of elasticity (4% decrease). As for concrete mixes with 100% fine RCA, a loss of 18.5% in the modulus of elasticity was registered. Similar effects were noticed by Ravindrarajah and Tam (1987).

Figure 3 presents the results of a study (Yang et al., 2008) on the effects of using either coarse or fine RCA on the modulus of elasticity of concrete. Concrete mixes produced with 100% fine RCA exhibited a loss of nearly 25% in the modulus of elasticity, whilst mixes produced with coarse RCA-1 at the same replacement level showed a near 10% decrease.

Nevertheless, the authors of another study (Limbachiya et al., 1998) suggested that by simply adjusting the w/c ratio it is possible for RAC mixes to achieve compressive strength and modulus of elasticity equivalent to those of a corresponding NAC. In this study when 100% coarse and 50% fine RCA were used in the production of concrete, a correction factor of 0.93 was applied to its w/c ratio to achieve mechanical performances equivalent to corresponding NAC.

4.3 Quality of the original material

As mentioned, the modulus of elasticity mainly depends on the aggregates and cement paste, specifically on their nature, as well as their bond and arrangement. In comparison to NA, RCA are less stiff due to the presence of old cement mortar, which has higher deformability than stone. Consequently, concrete produced with increasing replacement levels of RCA and relatively high mortar content has decreasing moduli of elasticity, as pointed out in section 4.1. However, the amount and quality of old mortar may vary significantly depending on the recycling processes used and strength of the original materials. Therefore, it is only natural that RA's with varying quality are capable of producing concrete mixes with different elastic moduli.

Figure 4a presents the moduli of elasticity of concrete with different target strength produced with RCA sourced from materials with varying strength classes (Hansen and Boegh, 1985). It is clear that RCA, from low strength concrete materials (RAC-L) caused a greater loss in the modulus of elasticity than when using RCA from high strength concrete (RAC-H).

In another study, Kou and Poon (2008) evaluated the effect of incorporating increasing RCA contents from different sources on the modulus of elasticity of concrete. Based on its composition, oven-dried density, water absorption and resistance to fragmentation, RCA-1 was considered to have the closest characteristics to those of NA, followed by RCA-3 and RCA-2. The incorporation of 100% coarse RCA-1, RCA-3 and RCA-2 led to modulus of elasticity decreases of 17%, 19% and 22%, respectively. This clearly showed a correlation between the decreasing quality of the three RA and the decreasing modulus of elasticity of mixes containing them.

Figure 4b shows the results of a more recent study (González and Etxeberria, 2014), in which the authors analysed the influence of adding RCA, from materials with different known strengths, on the properties of concrete with a target strength of 100 MPa. All mixes showed decreasing modulus of elasticity with increasing RCA content. However, this decrease was governed by the quality of the original concrete. The use of 100% coarse RCA sourced from 100 MPa concrete caused a reduction of 9% on the elastic modulus, whilst when using the same amount of RCA from 60 MPa and 40 MPa source concrete this decrease was of 20% and 26%, respectively.

Bogas et al. (2015) studied the influence of adding different replacement levels of RA obtained from crushed structural and non-structural lightweight concrete. The results showed that as the RA content increased, the modulus of elasticity also increased. Although these results contradict the rest of the literature review, it has a very simple explanation. Since the RA used in this study consist of a mixture of old adhered mortar and expanded clay lightweight aggregates, its resulting stiffness is higher than that of the lightweight aggregates alone, thus resulting in RAC with higher moduli of elasticity.

Yang et al. (2008), besides studying the effects of using either coarse or fine RCA on the modulus of elasticity of concrete, also studied the influence of their quality. Figure 3 shows that coarse RCA-1 were capable of producing RAC with greater modulus of elasticity than coarse RCA-2. This can be explained by the presence of a greater amount of cement mortar adhered to the surface of RCA-2, in comparison to RCA-1. Another interesting aspect found in this research is that, even though the literature review suggests that fine RA tend to have a greater influence on the modulus of elasticity, mixes produced with coarse RCA-2 and fine RCA showed similar losses in their moduli of elasticity. By analysing the RA's physical properties, it was found that these exhibited similar oven-dried densities and water absorption values. As demonstrated in other studies (Silva et al., 2014a, b), it is expected that concrete mixes produced with two different RA presenting similar properties exhibit comparable performance.

4.4 Influence of the mixing procedure

For conventional concrete mixes, it is normal for the producer to mix aggregates in a dry state, since their water absorption is generally very low (normally between 0.5% and 1.5%), and therefore relatively little water is required to compensate for the water absorbed by the NA during mixing. However, for RAC mixes, one should be fully aware of the high water absorption of RCA, due to the cement mortar adhered to its surface. Hansen (1992) suggested that RA should be introduced in a saturated and surface-dry condition. This prevents the RA from absorbing the free water that lends workability to the mix. Throughout the literature review, most researchers have produced RAC mixes with pre-saturated RA, allowing the production of RAC mixes with similar workability to that of control mixes. More recently, Etxeberria et al. (2007) suggested that RCA should be wetted, using a sprinkler system the day before mixing, up to a recommended level of humidity of 80%, whilst Mefteh et al. (2013) suggested that RCA can be prepared by watering them for 1 min. Naturally, it is also possible to produce RAC mixes with increasing RA content and with the same total w/c ratio as that of the control NAC, but this would lead to less workable mixes.

As an alternative to pre-saturating RA 24 h prior to mixing, Leite (2001) proposed the use of a simple water compensation method that can be used during concrete mixing. Since then, several authors (Amorim et al., 2012; Barbudo et al., 2013; Evangelista and de Brito, 2007, 2010; Ferreira et al., 2011; Fonseca et al., 2011; Matias et al., 2013; Pereira et al., 2012a, b), who have used this method, produced RAC mixes with minimum strength loss and equivalent workability to that of the control concrete, regardless of the replacement level. This method consists on the use of additional mixing water, which corresponds to the amount absorbed by RA, with the aim of keeping the free water content constant. Naturally, the additional water and time to absorb it depend on the aggregate's size and potential absorption capacity.

Ferreira et al. (2011) studied the influence of using pre-saturated and water compensated RCA in the production of concrete. The results showed that the water compensation method is capable of producing RAC mixes with more stable levels of consistency and with slightly improved compressive strength. The modulus of elasticity of RAC mixes produced with the water compensation method exhibited slightly higher values for RCA contents between 20% and 50%. This improvement was explained by a "nailing effect", which results from the penetration of cement paste inside superficial pores of RCA particles. Prior to mixing, pre-saturated RCA exhibited not only a high level of humidity but also water on the surface and within surface pores. This may have impaired the penetration of the cement paste into the pores and caused a decrease of the "nailing effect" and, consequently, a weaker ITZ between cement paste and RCA.

Other authors (Tam et al., 2005; Tam et al., 2006; Tam and Tam, 2007; Tam et al., 2007) proposed a slightly different approach for the production of RAC. Instead of the normal mixing approach (NMA), in which all components are placed inside the mixer at the same time, it had been proposed dividing it in two stages (two stage mixing approach - TSMA). The TSMA consists of pre-wetting the RA before adding the cement, in order to strengthen the weak bond of RA with the new cement paste. The concept behind this mixing procedure, which is similar to the one previously mentioned, is that it allows the cement slurry to coat the RA, thus providing a stronger ITZ by filling the cracks and pores within them. Test results showed considerable improvement in compressive strength (strength increase between 10% and 20% for a replacement level of 30%) (Tam et al., 2005). These authors also found that, for the same replacement level and mix design, by simply allowing the RCA to absorb part of the mix water before adding the cement (TSMA), it was possible to produce RAC mixes with slightly higher modulus of elasticity than when using NAM (average modulus of elasticity increase of 8%).

4.5 Exposure to different environmental conditions

Experimental research (Amorim et al., 2012; Buyle-Bodin and Hadjieva-Zaharieva, 2002; Dhir et al., 1999; Fonseca et al., 2011) has been made on the effect of different environmental conditions on the properties of RAC mixes, relative to the corresponding NAC. It has been observed that RAC mixes had parallel strength development to NAC, regardless of the environmental condition. In other words, the influence of the curing process on concrete strength appears not to have been affected by the presence of RA.

This phenomenon was also observed to some extent in the modulus of elasticity. Fonseca et al. (2011) studied the influence of curing conditions to the properties of concrete produced with increasing coarse RCA content. The results of this study showed that fully replaced concrete mixes exhibited slightly lower losses after being cured in a laboratory environment (the driest environment of the four). The authors of this study suggested that the presence of compensating water within the RCA offset the loss in modulus of elasticity of concrete subjected to a drier environment. This allowed a proper hydration of cement particles, thus improving the RAC's mechanical performance. Nevertheless, the difference of the relative modulus of elasticity between RAC and NAC cured in different environments is very low. Therefore, for all practical purposes it can be said that the curing process had marginal influence on the elastic modulus of concrete containing RA.

4.6 Chemical admixtures

Recycled concrete mixes generally need a greater amount of water to maintain the same workability as that of an equivalent NAC composition, due to the relatively high water absorption of RA and sometimes their rougher surfaces. Nevertheless, it is possible to obtain workable RAC mix with the same total w/c ratio as that of the control NAC, simply by controlling the amount of superplasticizers (Prakash and Krishnaswamy, 1998).

Juan and Gutiérrez (2004) conducted a study on the effect of superplasticizers on the mechanical performance of RAC with increasing RCA content. Figure 5a presents the comparison of the modulus of elasticity of concrete mixes with increasing RCA content with the same cement content, but with increasing superplasticizer contents. The results show that, regardless of the superplasticizer content, there is a parallel development of the modulus of elasticity with increasing replacement levels. This means that the use of increasing superplasticizer contents appears to have marginal influence on the modulus of elasticity of concrete mixes with increasing RCA content.

In another research, Pereira et al. (2012b) studied the effects of incorporating two types of water-reducing admixtures (i.e. a regular one, WRA, and a high-range water-reducing one, HRWRA) on the mechanical performance of concrete containing fine RCA. Figure 5b presents the modulus of elasticity of concrete mixes using these admixtures and with increasing RCA content. The results show that concrete mixes made with HRWRA exhibited similar losses of the modulus of elasticity with increasing replacement levels, when compared to mixes without chemical admixtures. However, mixes containing WRA exhibited a greater loss in the modulus of elasticity with increasing RCA content, in comparison to the other two series. Further research is required to ascertain whether this is a generalized trend or if indeed concrete mixes display parallel development of the modulus of elasticity with increasing RCA content, regardless of the water reducing admixtures' power and content.

4.7 Additions incorporation

It is known that using fly ash as cement replacement will cause a decline of the mechanical performance of concrete with a relatively early age. A study by Kou et al. (2007) suggested that this effect may vary with increasing replacement levels of NA with RCA. Figure 6 presents the modulus of elasticity of concrete mixes with increasing coarse RCA and fly ash content. As expected, as the fly ash content increased, the modulus of elasticity decreased for NAC mixes (Figure 6a). However, as the coarse RCA content increased, concrete specimens began displaying similar moduli of elasticity, regardless of the fly ash content. Figure 6b shows that for the same replacement level of 100% coarse RCA, concrete mixes produced with 0%, 25% and 35% fly ash content, the modulus of elasticity decreased around 40%, 35% and 25%, respectively, relative to the control concrete.

Contrary to that observed in the previous study (Kou et al., 2007), Kou et al. (2008) obtained concrete mixes with higher modulus of elasticity after incorporating fly ash. This can be easily explained by the fact that, in their first study (Kou et al., 2007), they replaced part of the cement with fly ash, whereas in the second (Kou et al., 2008) they added it to the existing amount of cement, thus obtaining a greater amount of binder content. This increase in the modulus of elasticity was of 10%, 9%, 13% and 14% for concrete mixes prepared with 100% coarse RCA and with w/c ratios of 0.55, 0.50, 0.45 and 0.40, respectively. The results of this study also showed that the elastic modulus decreased with increasing RCA content, but increased with a decrease in the w/c ratio. Furthermore, regardless of the w/c ratio, the modulus of elasticity of concrete mixes with increasing coarse RCA content was parallel between those produced with fly ash and those without it. These results suggest that the incorporation of increasing amounts of RCA has no effect on the elastic modulus development of concrete mixes containing fly ash.

Corinaldesi and Moriconi (2009) studied the influence of adding mineral additions on the performance of concrete containing 100% MRA (70% RCA, 27% RMA and 3% of contaminants) as substitute of fine and coarse NA. The authors observed that the static moduli of elasticity mainly depend on the concrete’s strength and are not significantly influenced by the presence of mineral additions. The dynamic modulus of elasticity was found to be mainly influenced by the type of aggregate used, but not so much by the presence of mineral additions. Furthermore, the authors observed that the test method for evaluating the dynamic modulus of elasticity tends to underestimate the elastic modulus of RAC since it could only detect the presence and amount of voids in the material, but not the quality of the ITZ between the cement paste and RA.

The simultaneous use of ground granulated blast furnace slag (GGBS) as cement replacement and RCA in the production of concrete was studied by Berndt (2009). The dynamic moduli of elasticity of NAC mixes produced with 100% ordinary Portland cement (OPC) and with a binder containing 50% OPC and 50% GGBS mixes were equivalent (47.2 GPa and 47.4 GPa, respectively). Replacing the cement at 70% by GGBS caused a slight reduction in the dynamic modulus (around 4% to 45.6 GPa), relative to the two previously stated. However, when the coarse aggregate fraction was fully replaced by coarse RCA, the moduli of elasticity decreased almost in a parallel manner. These results suggest that the presence of RCA has a marginal influence on the effect of adding GGBS in concrete.

4.8 Development over time

Similarly to compressive strength, the modulus of elasticity depends on the age of concrete, because the cement paste hardens over time with the consecutive hydration reactions of cement particles. In the case of RAC mixes, it has been suggested (Corinaldesi and Moriconi, 2009; Etxeberria et al., 2006; Tam et al., 2005) that these hydration reactions in the ITZ between the new cement paste and RCA are the cause of an improved bond strength. This may be explained by the internal curing effect caused by the water, initially absorbed by RCA, moving to the new cement paste and to unhydrated cement particles contained in the old adhered mortar and thus resulting in new calcium-silicate-hydrates (C-S-H). The newly formed

C-S-H can gradually fill the ITZ region and effectively improve the ITZ bond strength between the RCA and new cement paste (Poon et al., 2004; Sakata and Ayano, 2000), thus resulting in slightly improved mechanical performance.

The results of a study by Poon and Kou (2010) on the development of the mechanical performance of concrete over the course of 10 y, with increasing replacement levels and varying fly ash content, are shown in Figure 7. As expected, all concrete mixes showed an increase of the modulus of elasticity over time (increase of 5 GPa to 10 GPa between 28 d and 10 y). RAC mixes with 100% coarse RCA showed a decrease between 5 GPa and 10 GPa, relative to the corresponding NAC mixes. This gap was constant over the course of years. In other words, the modulus of elasticity of RAC mixes develops in parallel with that of the corresponding NAC mixes. Furthermore, the addition of increasing fly ash content, as partial replacement for cement, did not cause any special effect on the modulus of elasticity development over time of mixes with increasing coarse RCA content.

5 Predicting the modulus of elasticity of recycled aggregate concrete by means of a performance-based classification

There is considerable discrepancy in the literature concerning the loss in modulus of elasticity (E_{cm}) of RAC relative to the corresponding NAC. It is clear that some aspects related to the use of RA in concrete still elude researchers. Despite the fact that some authors (de Brito and Robles, 2010; Dhir et al., 2004; Dhir and Paine, 2007; Kikuchi et al., 1998; Teranishi et al., 1998) have emphasized that certain RA have distinct characteristics and that these should be used accordingly, the literature review has shown that RA are used with no criteria and no regard to their quality. Therefore, a statistical analysis was performed on the collated data in order to develop a model for predicting the effect of increasing content of RA with known quality on the E_{cm} value of concrete.

After an evaluation of the results presented in Figure 2, it was perceived that these were not enough to establish effective correlations that could fully explain the disparity in the moduli of elasticity of RAC. Therefore, the authors created Figure 8 by separately plotting the coarse and fine RA of Figure 2. The maximum recorded losses in the moduli of elasticity of concrete produced with 100% or coarse or fine RA were just below 45%. However, the lower limit of the 95% confidence interval in Figure 8a suggests that RAC mixes may exhibit a maximum loss of 56%. This may be because the RAC mixes exhibited a greater than expected loss in E_{cm} in low replacement levels, and therefore this trend propagated to greater replacement levels. These results suggest that the discrepancy of the moduli of elasticity of RAC mixes cannot merely be explained on the basis of RA size, and therefore further analysis of the data is required to explain the results.

Figure 9 presents an analysis of the 95% confidence limits, similar to Figure 8a, but in terms of the RA type. By observing the average losses in the moduli of elasticity it is unclear which RA type is capable of producing concrete with an elastic modulus similar to that of NAC. According to the literature review, RCA is the answer to this question, since it is sourced from materials similar to those in which they are being used, i.e. there is greater compatibility, and normally exhibit lower porosity levels, which result in higher E_{cm}. The scatter of the results can be explained by RCA sourced from source concrete with varying moduli of elasticity, or which have been subjected to insufficient recycling procedures and thus exhibit greater amount of deformable old mortar. These results suggest that the loss in E_{cm} with increasing RA content cannot also be fully explained on the basis of RA type. For this reason, the data were further analysed with respect to the quality of RA.

In their previous study (Silva et al., 2014b), the authors were able to produce a performance-based classification using the relationship between the water absorption (WA) and oven-dried density (ODD) of RA (Table 2). This was made possible by means of a statistical analysis performed on 589 aggregates of different types, sizes and origins, sourced from 116 publications. The use of this simple methodology provides a means to measure the quality of RA based on their easily accessible physical properties. In other words, instead of classifying RA solely based on their composition, which is proposed by some of the current specifications (BRE, 1998; DIN-4226, 2002; LNEC-E471, 2006; NBR-15.116, 2005; OT-70085, 2006; WBTC-No.12, 2002), it allows classifying them based on their quality as well. In another study (Silva et al., 2014a), this classification system was used to measure the quality of RA and analyse its effect on the compressive strength (f_{cm}) of concrete. The results showed strong to very strong correlations which allowed producing a generic prediction model of the f_{cm} of concrete with increasing coarse RA of known quality.

Using this performance-based classification, Figure 10 was made. It shows the E_{cm} of concrete with increasing RA content of known quality (Class A, B, C and D). Figure 10a, which was based on 31 concrete mixes from 5 studies, shows that the use of 100% coarse class A RA allows the production of concrete with an average loss in E_{cm} of around 11%. As the quality worsened there was a greater variability in the results, i.e. the 95% confidence interval increased as the content of lower quality RA increased. In Figure 10d, for example, the lower limit of the 95% confidence interval suggests that mixes using 100% class D RA (normally composed of RMA) would lead to a maximum loss of 80%. However, the maximum recorded loss in E_{cm} of mixes using 100% coarse RA was of around 40%. As previously mentioned, this may be explained by greater than expected loss in E_{cm} in low replacement levels, whose trend propagated to greater replacement levels.

Despite the results' scatter, Figure 10 suggests that the E_{cm} of concrete depends on characteristics other than the type and size of RA. Indeed, the quality of the RA, which can be measured using the performance-based classification (Silva et al., 2014b), is a factor that also needs to be accounted for when producing RAC. Indeed, by observing Figure 11 it is clear that, in each of the individual studies (Akbarnezhad et al., 2011; Dhir and Paine, 2007; Kou and Poon, 2008; Yang et al., 2008), the authors were able to produce concrete mixes with different moduli of elasticity using coarse RCA of different quality. The use of 100% coarse class A RCA, produced mixes with moduli of elasticity between 0.89 and 0.92 times that of the corresponding NAC, whilst for class B RCA the range of these values was of 0.72 to 0.86.

6 Relationship between the E_{cm} and f_{cm} of recycled aggregate concrete

According to EC2 (2008), the elastic deformations of concrete mostly depend on its composition, especially its aggregates. For this reason, the E_{cm} of a concrete specimen depends on the elastic modulus of each of its components. EC2 (2008) thus considers the possibility of producing concrete using NA of different geological origin: basalt, quartzite, limestone and sandstone. In this standard, it is considered that, for the same f_{cm} and mix design, a concrete specimen made with different kinds of NA will exhibit varying moduli of elasticity. For this reason, it is reasonable to assume that RA's of different size, type and quality have a predictable effect on the E_{cm} of concrete.

When designing and building structures, project and field engineers often use a simple formula to determine the E_{cm} by means of the f_{cm} of a given concrete mix. The relationship between these two properties, despite looking different in current standards for structural concrete (ACI-318, 2002; CEB-FIP, 1990; EHE-08, 2010; EN-1992-1-1, 2008), exhibit similar development.

Over the years, various researchers (Cabral et al., 2010; Dhir et al., 1999; Dillmann, 1998; Kakizaki et al., 1988; Mellmann et al., 1999; Ravindrarajah and Tam, 1987; Xiao et al., 2006; Zilch and Roos, 2001) proposed formulas that could explain the relationship between the E_{cm} and f_{cm} of RAC mixes (Figure 12). However, these do not account for the replacement level, which has a significant impact on the E_{cm}. Meanwhile, attempts were made by the Task Force of the Standing Committee of Concrete of Spain (2004) to estimate the E_{cm} based on the replacement level and on the nature of the rock used for the production of the source concrete. The authors of this publication proposed the addition of a correction factor based on the replacement level (1.00 for concrete mixes containing 20% coarse RA of controlled quality and 0.80 for mixes containing 100% coarse RA) to the equation proposed by the EHE-08 (2010).

Figure 13 presents the relationship between the E_{cm} and f_{cm} of 588 concrete mixes produced with either coarse or fine RA of different quality and type, sourced from 43 publications. Most of the RAC mixes (around 80%) are above the EC2 curve for sandstone aggregates. Most of the values below this curve belong to two studies (Dhir and Paine, 2007; Limbachiya et al., 2012), in which most of the values of the control NAC mixes were below the curve as well. After discarding these values, it was found that 95% of the values were above the relationship proposed by the EC2 using a correction factor equal to 0.71 (including those values, this correction factor would have been 0.61), which for practical purposes can be rounded to 0.7. In other words, there is a 95% chance that the E_{cm} of a RAC mix with known f_{cm} is above the EC2 curve corresponding to sandstone aggregates.

According to the literature review and the results in section 5, the use of increasing RA content has a significant impact on the E_{cm}, and more so if these exhibit low quality. Two studies were found (Juan and Gutiérrez, 2004; Kou et al., 2008), in which the authors evaluated the effect of including an increasing amount of coarse RCA on the properties of concrete produced with a wide range of w/c ratios, thus enabling making Figures 14 and 15. The coefficients of correlation (or Pearson's r) were within the range 0.701-0.981. From a statistical point of view, according to Piaw (2006), having obtained such coefficients means there is either a strong ($0.7 < |r| \leq 0.9$) or very strong ($0,9 < |r| < 1$) correlation between E_{cm} and f_{cm}.

By comparing the figures, it is clear that for the same f_{cm}, mixes in Figure 15 present a greater loss in E_{cm} with increasing coarse RCA content, than those in Figure 14. This may be because of the lower quality RCA (lower ODD and higher WA) used in the first study (Kou et al., 2008). These results show that even though all values were within the EC2 curves for basalt and sandstone aggregates, the elastic moduli showed a great disparity for mixes using increasing coarse RCA content. Therefore, it is suggested that further research is made on the effect of using increasing amount of RA with known quality (according to the performance based classification (Silva et al., 2014b)) on the modulus of elasticity of RAC. This would become a step forward in determining more suitable correction factors that engineers can relate to when designing and building concrete structures. In concrete design, the modulus of elasticity has a vital role in the serviceability limit state, in order to control the deformation of concrete. From a structural point of view, the stiffness of the elements is proportional to the third power of the relationship between its height and thickness. Therefore, the loss of stiffness in a concrete beam, for example, can be easily compensated with a slight increase of its height.

7 Conclusions

The scope of this investigation included an examination of the main factors of RA that influence the modulus of elasticity of concrete and a statistical analysis of data available in the literature, which enabled establishing a relationship between the modulus of elasticity and compressive strength of recycled aggregate concrete and facilitating the structural designers' option for this type of concrete. Based on the results of this investigation, the following conclusions can be drawn:

- The modulus of elasticity normally decreases with increasing RA content, the degree of which depends on characteristics inherent to RA, i.e. type, size and quality of the original material.
- RCA normally produce RAC mixes with the lowest average loss in the elastic modulus, followed by MRA and RMA. Since RMA usually have lower oven-dry

density and higher water absorption values, as the content of this material increases, it is expected that the modulus of elasticity will decrease.

- The use of several crushing stages on concrete makes the coarse fraction of RCA lose part of its adhered mortar, which remains in the finer fraction. Because of this, fine RCA exhibit relatively low elastic moduli, and therefore these will have a more deleterious effect on the modulus of elasticity than the coarse fraction.
- As the strength and stiffness of the original material increase, it is expected that RA obtained from them produces concrete with lower losses in the modulus of elasticity.
- The use of a water compensation method during mixing was found to produce RAC with lower losses in the modulus of elasticity, due to the improved ITZ between RA and new cement paste.
- Over a long period of time, regardless of the RA and fly ash contents, RAC mixes are expected to present a parallel development of the modulus of elasticity in comparison to that of corresponding NAC mixes.
- In order to predict the modulus of elasticity of concrete, apart from the size and type of RA, its quality is a factor that also needs to be taken into consideration. The performance-based classification of RA proved to be an effective and practical means of measuring the quality of RA for use in concrete. By ranking RA on the basis of both their composition and their quality, it is possible to predict the modulus of elasticity of concrete with increasing content of RA of known quality.
- The statistical analysis performed on the relationship between the modulus of elasticity and compressive strength shows that even though RAC may exhibit similar compressive strength to corresponding NAC mixes, as the RA content increases the modulus of elasticity decreases. However, for a given compressive strength, most studies obtained moduli of elasticity of RAC above the proposed EC2 curve for

sandstone aggregates. This means that even when high RA replacement levels are used in the production of concrete the resulting RAC will generally have moduli of elasticity compliant with existing standards and specifications for NAC.

Acknowledgements

The authors are grateful for the support of the ICIST Research Institute, IST, University of Lisbon and FCT (Foundation for Science and Technology).

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Table captions

Table 1 - Composition of recycled aggregates sourced from construction and demolition wastes

Table 2 - Physical property requirements of the performance-based classification (Silva et al., 2014b)

Table 1 - Composition of recycled aggregates sourced from construction and demolition wastes

Recycled concrete aggregates (RCA)	Minimum of 90%, by mass, of Portland cement-based fragments and natural aggregates.
Recycled masonry aggregates (RMA)	Minimum of 90%, by mass, of the summation of the following materials: aerated and lightweight concrete blocks; ceramic bricks; blast-furnace slag bricks and blocks; ceramic roofing tiles and shingles; and sand-lime bricks (Hansen, 1992).
Mixed recycled aggregates (MRA)	Composed of less than 90%, by mass, of the summation of the two aforementioned RA.

Table 2 - Physical property requirements of the performance-based classification (Silva et al., 2014b)

Aggregate class	A			B			C			D
	I	II	III	I	II	III	I	II	III	
Minimum oven-dried density (kg/m^3)	2600	2500	2400	2300	2200	2100	2000	1900	1800	No limit
Maximum water absorption (%)	1.5	2.5	3.5	5	6.5	8.5	10.5	13	15	
Maximum LA abrasion mass loss (%)	40			45			50			

Figure captions

Figure 1 - Effect of increasing RA content on the modulus of elasticity, based on data from: a) Dhir and Paine (Dhir and Paine, 2007); b) Gomes and de Brito (Gomes and de Brito, 2007; Gomes and de Brito, 2009)

Figure 2 - Effect of incorporating increasing RA content on the relative modulus of elasticity of concrete

Figure 3 - Increasing RCA content of different sizes and quality, based on data from (Yang et al., 2008)

Figure 4 - Effect of RCA from different sources on the modulus of elasticity, based on data from (a) Hansen and Boegh (1985) and (b) González and Etxeberria (2014)

Figure 5 - Effect of adding superplasticizers on the modulus of elasticity of concrete, based on data from: a) Juan and Gutiérrez (2004); b) Pereira et al. (2012b)

Figure 6 - Modulus of elasticity of concrete with increasing coarse RCA and fly ash content, based on data from (Kou et al., 2007)

Figure 7 - Modulus of elasticity over time of concrete mixes with increasing coarse RCA content and varying fly ash content: a) No fly ash; b) 25% fly ash; c) 35% fly ash; 55% fly ash based on data from (Poon and Kou, 2010)

Figure 8 - Effect of incorporating increasing coarse (a) and fine (b) RA contents on the relative modulus of elasticity of concrete

Figure 9 - Effect of incorporating increasing coarse RCA (a), RMA (b) and MRA (c) contents on the relative modulus of elasticity of concrete

Figure 10 - Effect of introducing increasing Class A (a), B (b), C (c) and D (d) RA on the relative modulus of elasticity of concrete

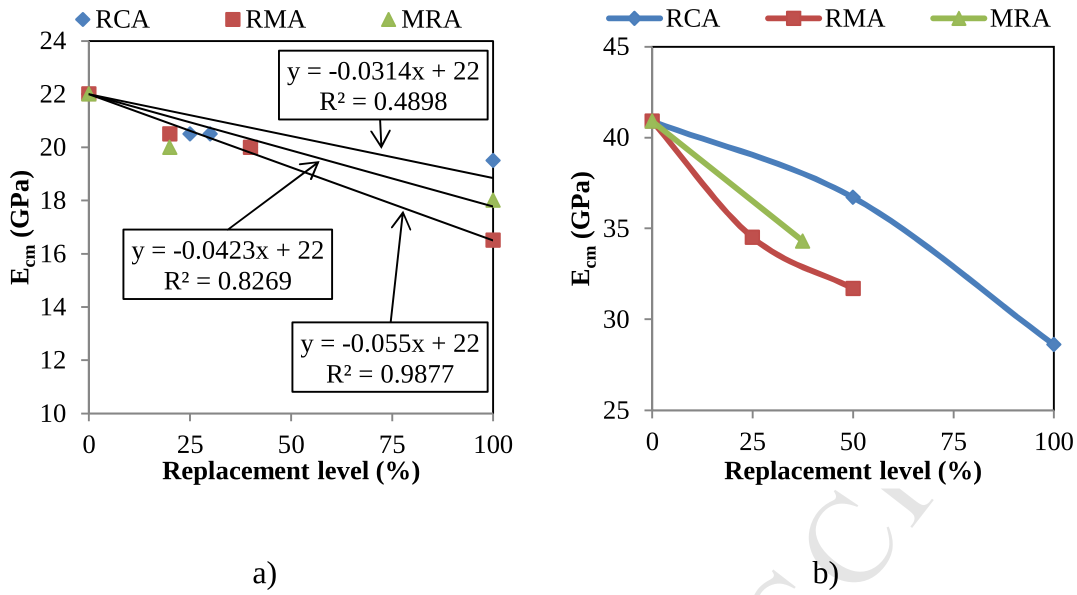
Figure 11 - Effect of incorporating increasing coarse RA on the relative modulus of elasticity of concrete, based on data from: a) Akbarnezhad et al. (2011); b) Yang et al. (2008); c) Dhir and Paine (2007) and; d) (Kou and Poon (2008))

Figure 12 - Relationship between Ecm and fcm

Figure 13 - Comparison of the relationship between Ecm and fcm from the literature review and those proposed by EC2

Figure 14 - Relationship between Ecm and fcm of concrete mixes with increasing replacement levels, based on data from (Juan and Gutiérrez, 2004)

Figure 15 - Relationship between Ecm and fcm of concrete mixes with increasing replacement levels, based on data from (Kou et al., 2008)



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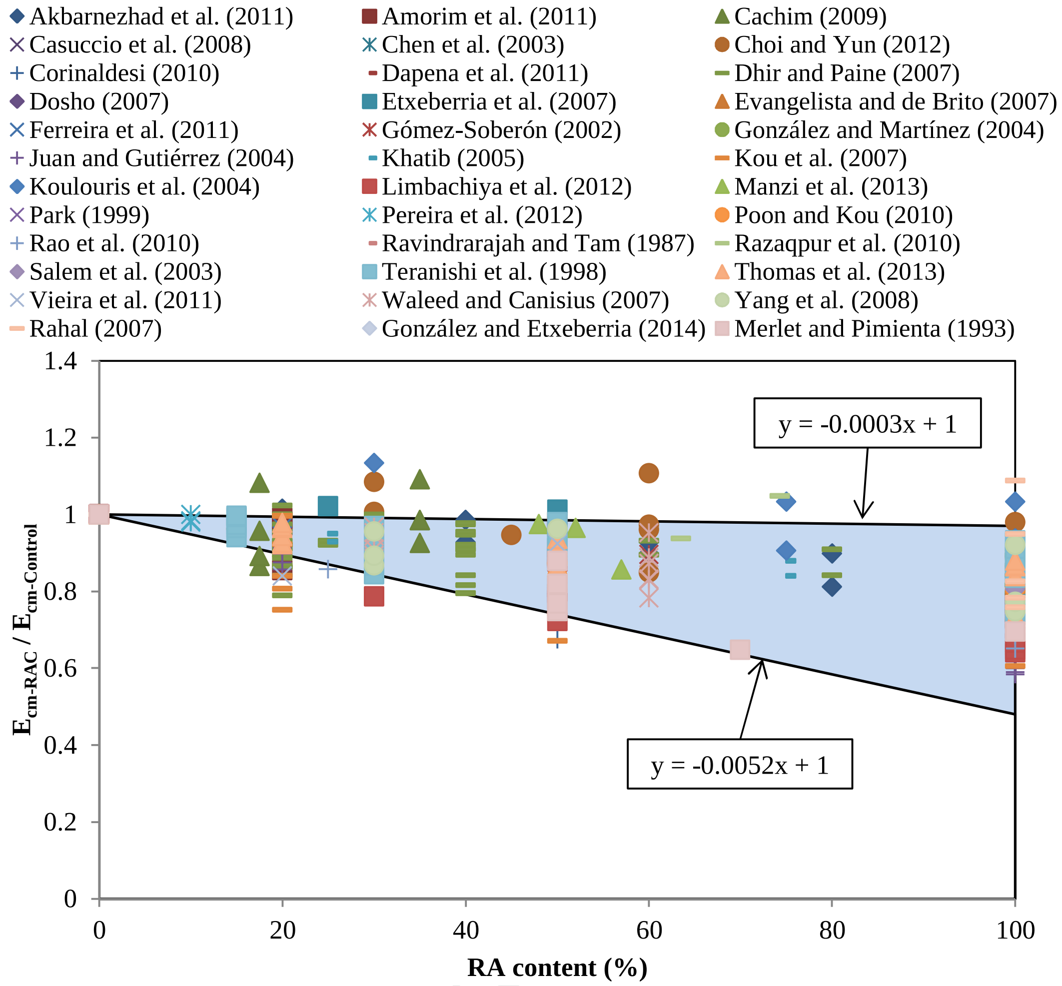

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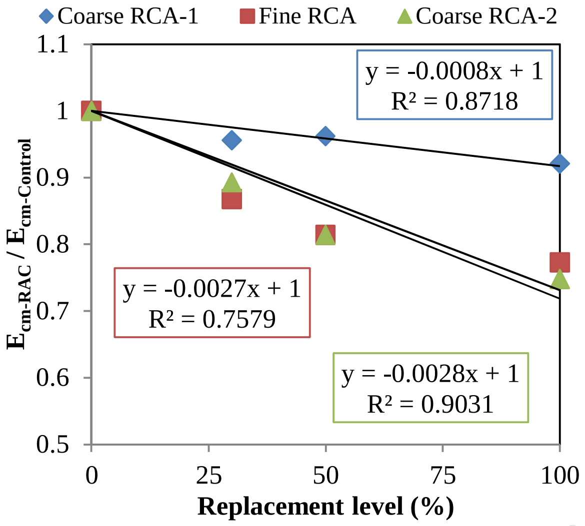

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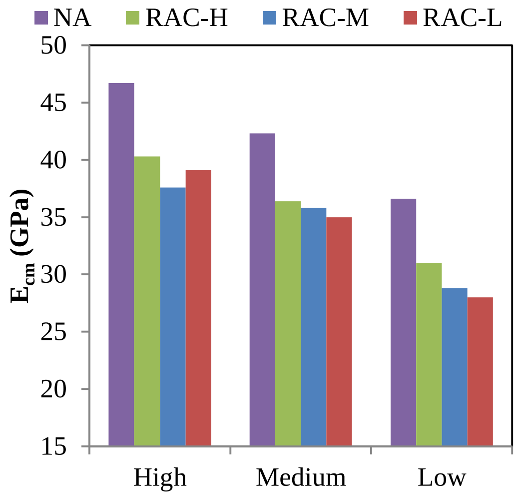
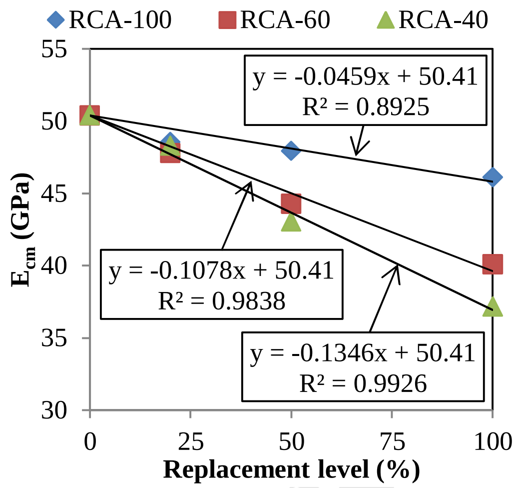


a)



b)

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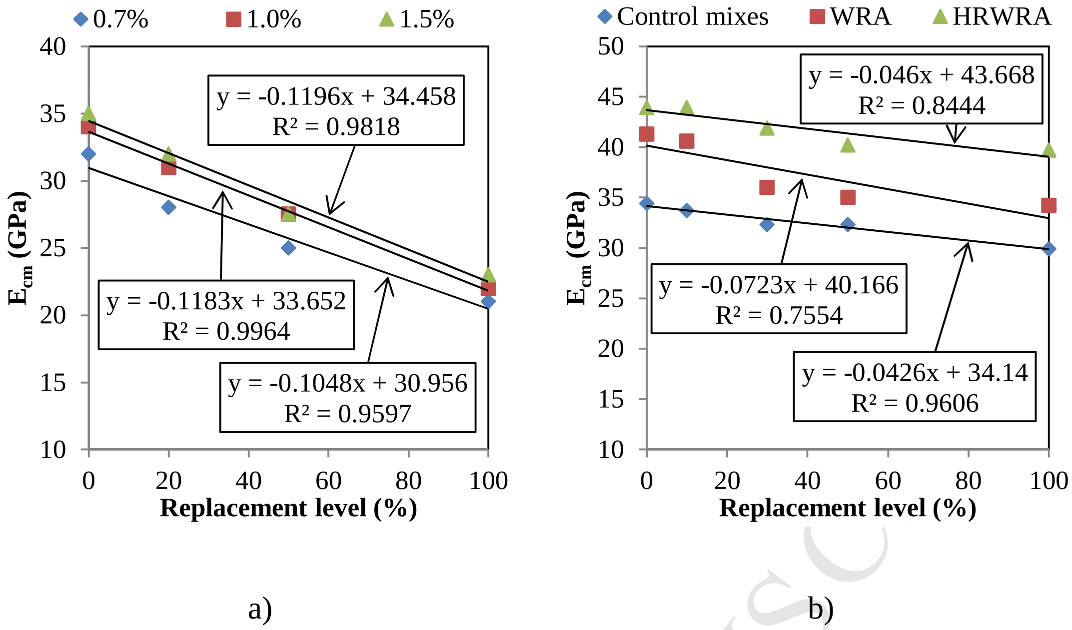

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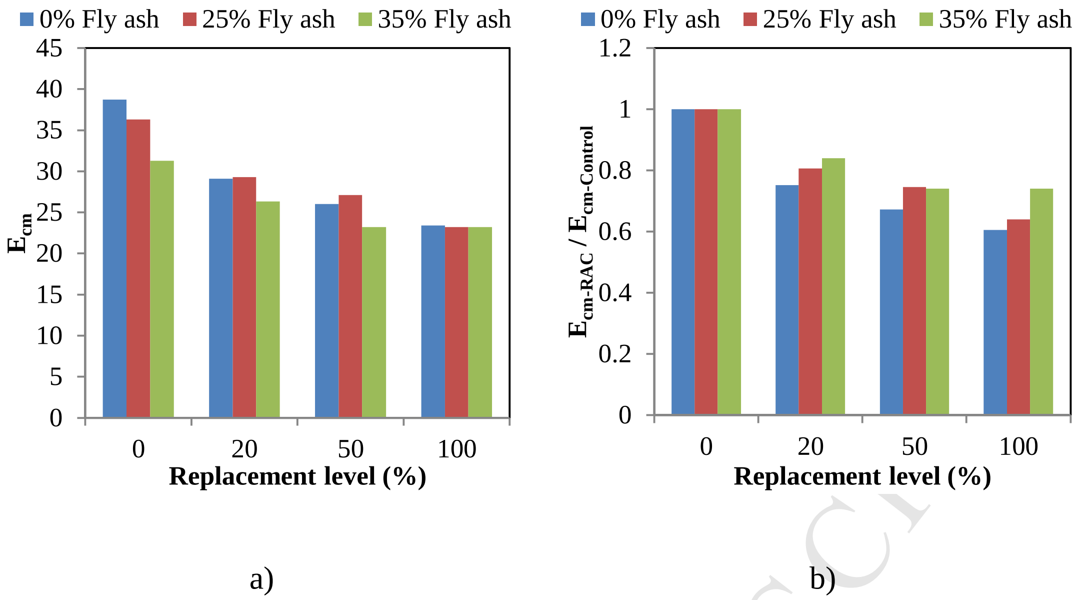

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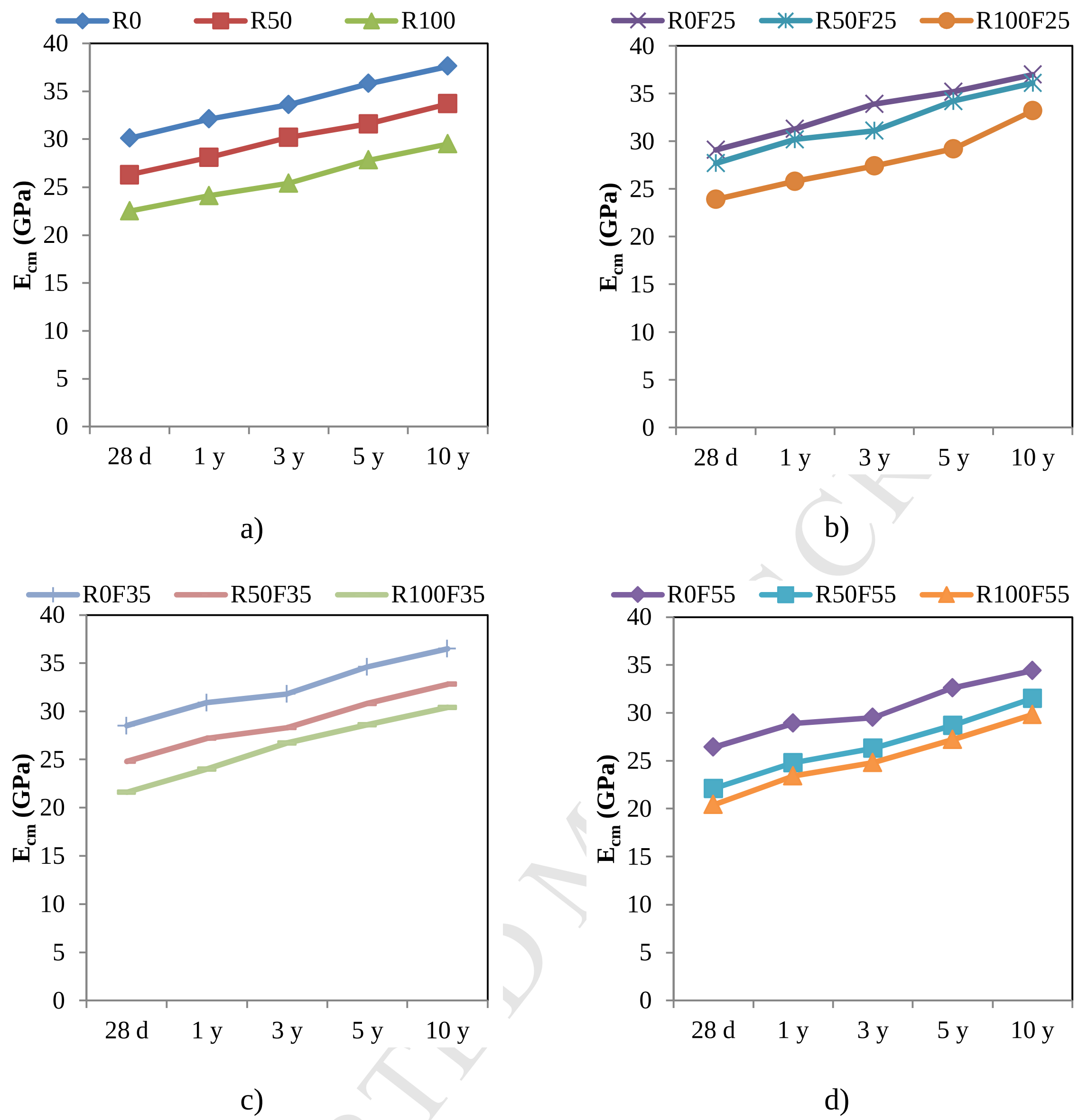

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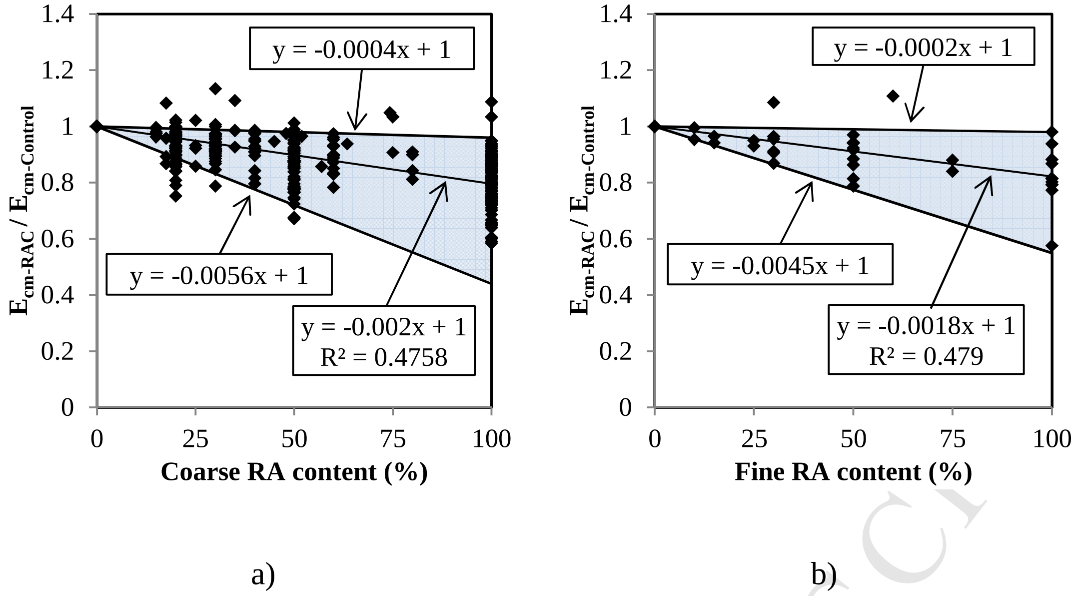

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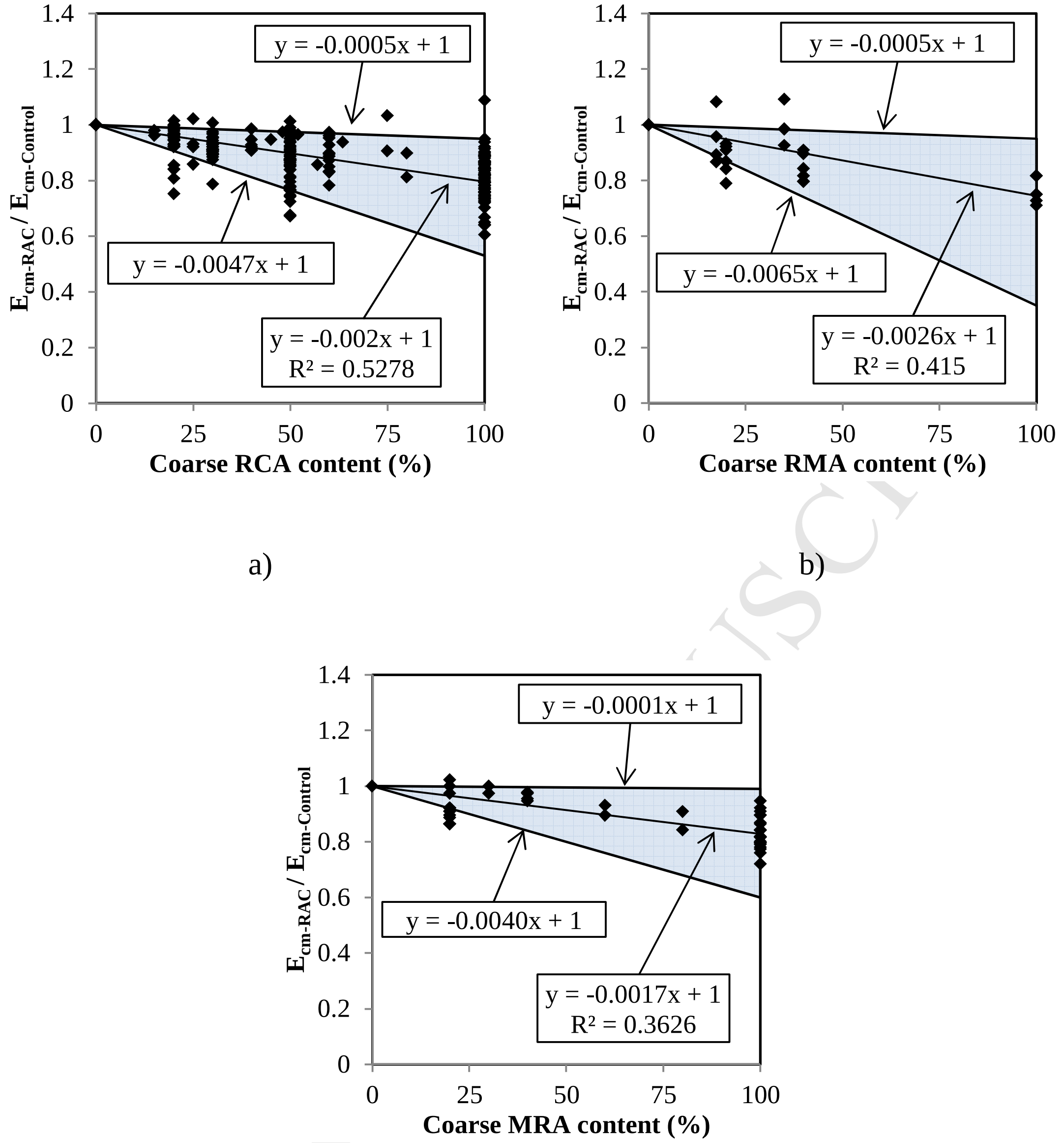

a) b)

c)

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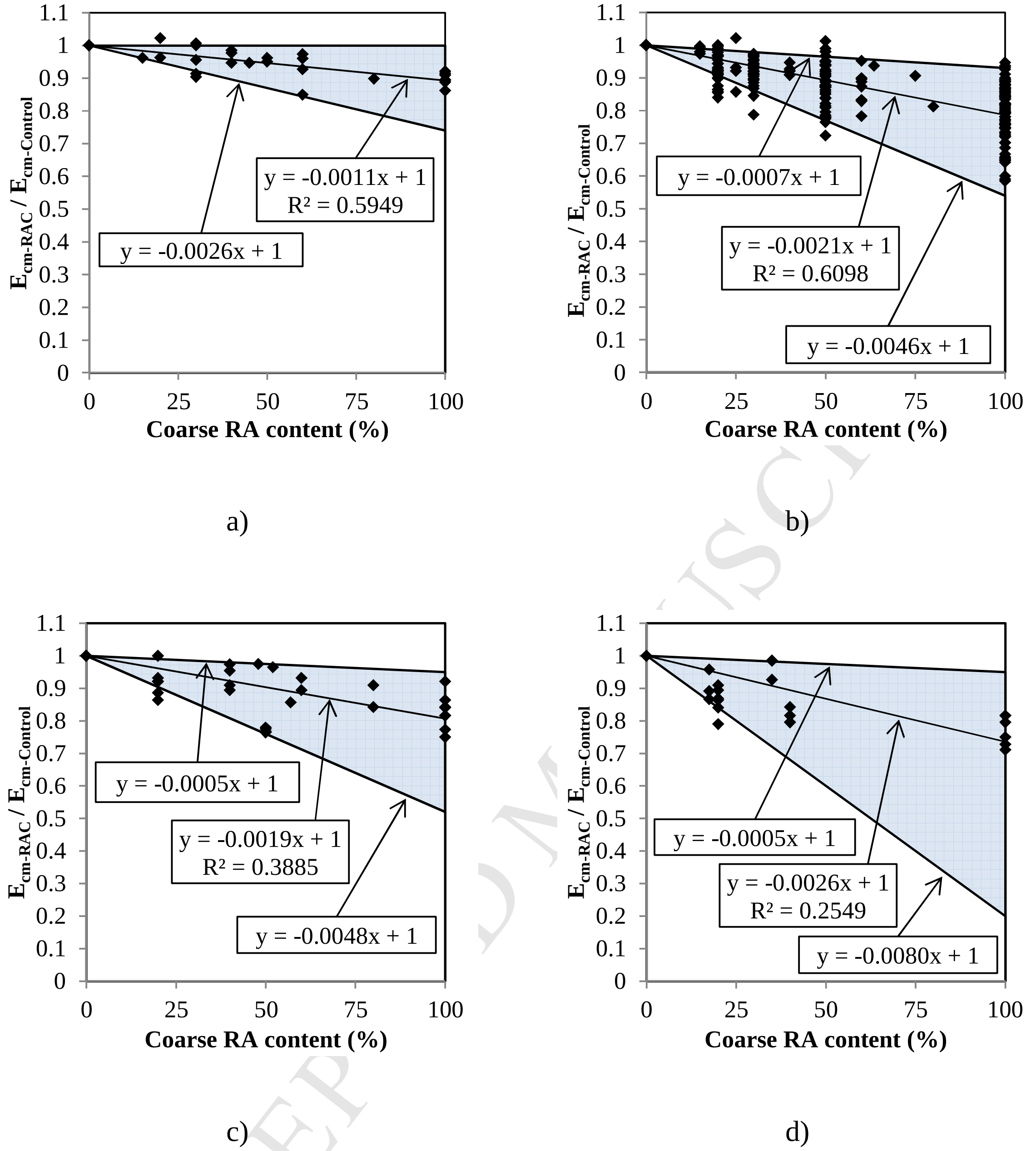

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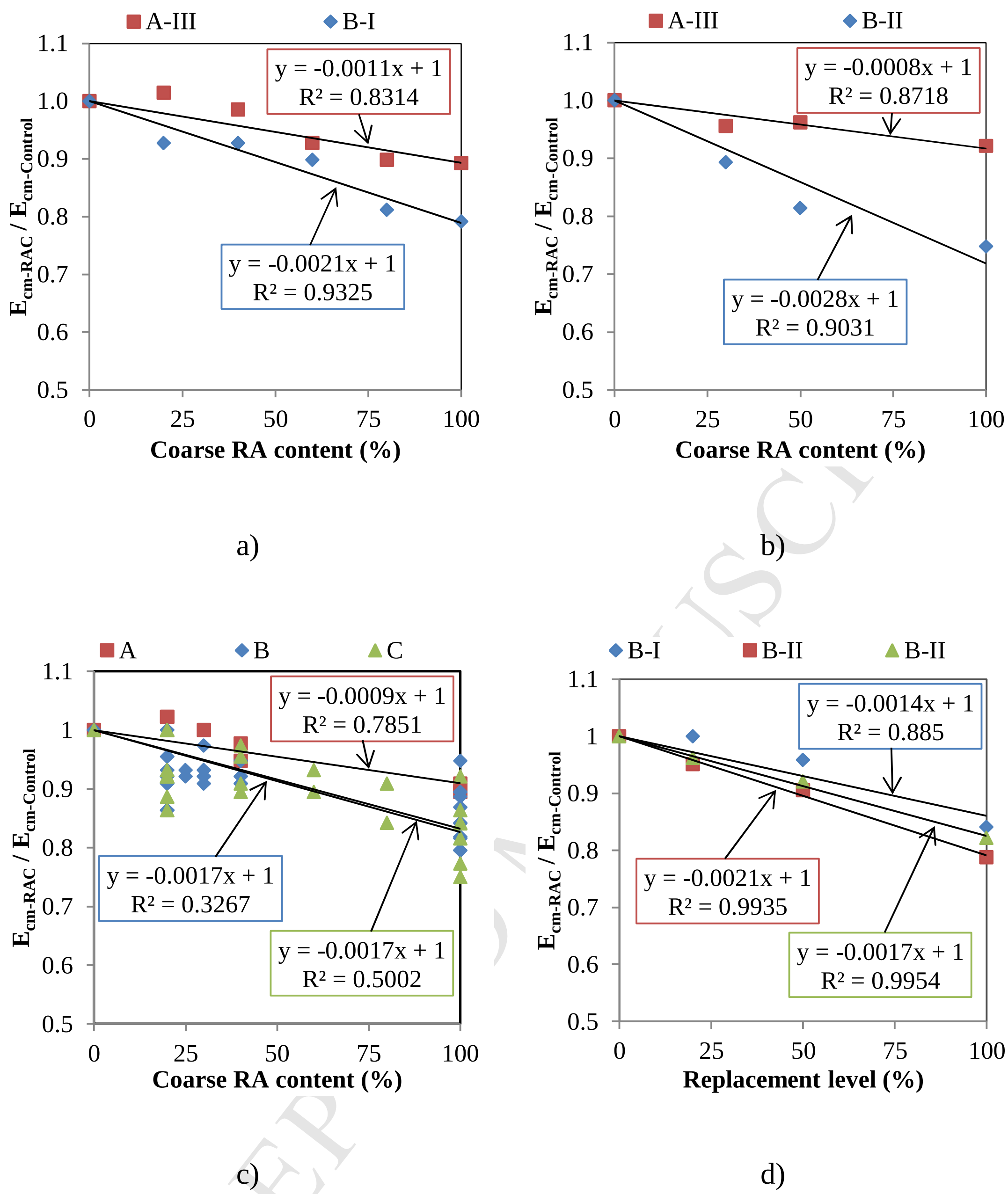

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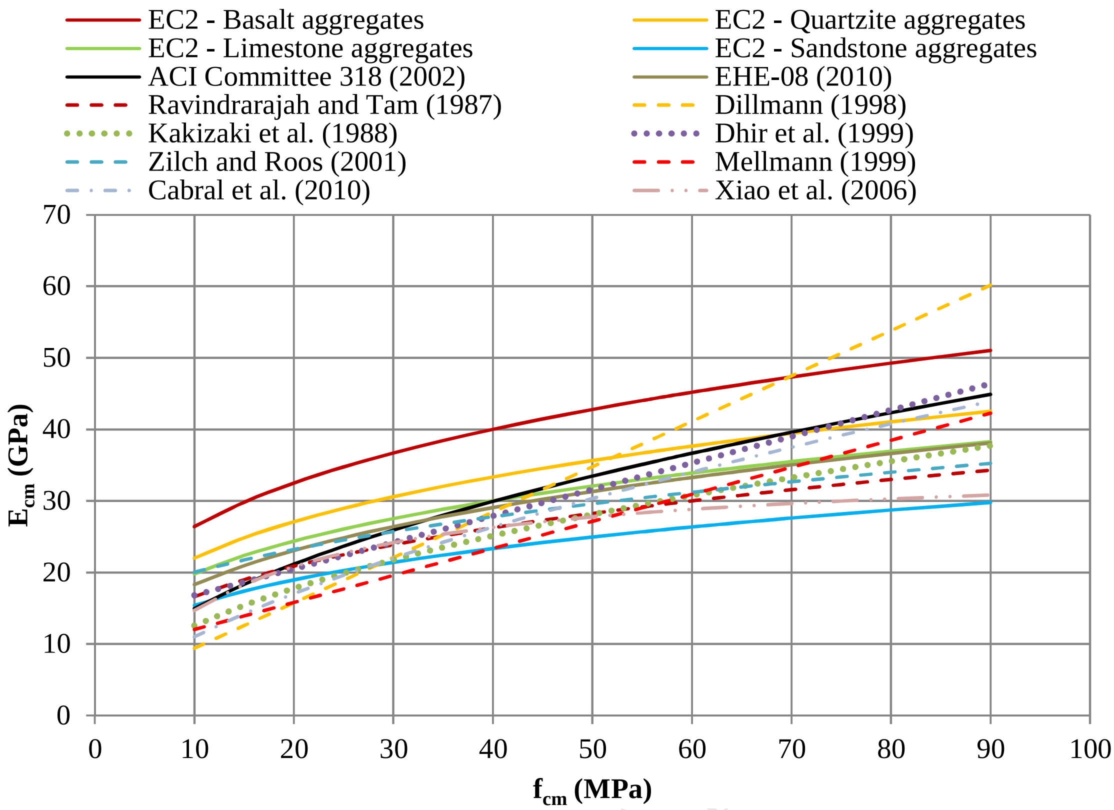

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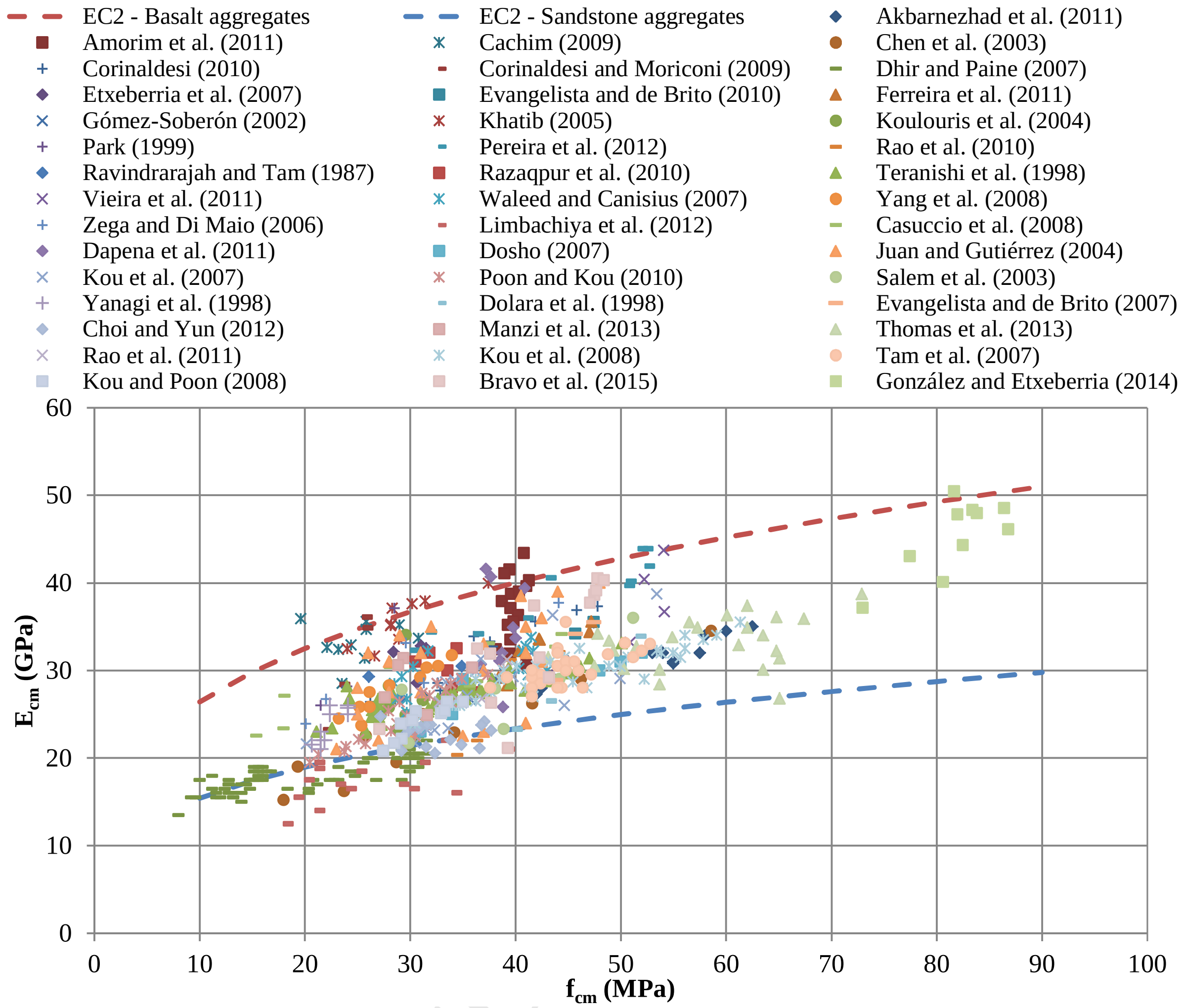

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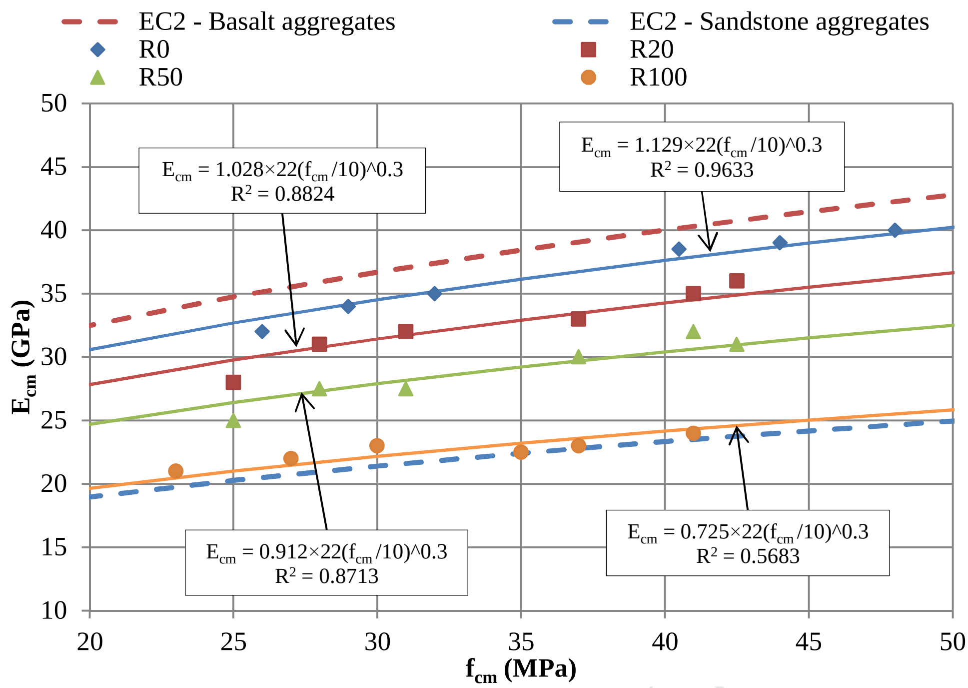

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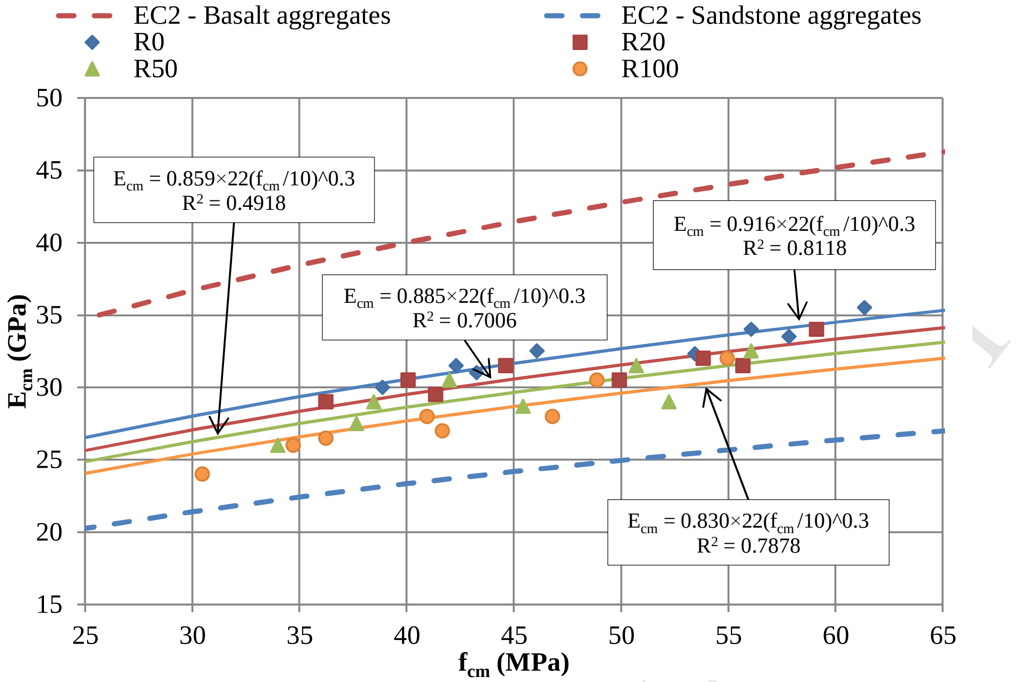

Figure 15 - Relationship between E_{cm} and f_{cm} of concrete mixes with increasing replacement levels, based on data from (Kou et al., 2008)

Research Highlights

- Systematic literature review on the elastic modulus of recycled aggregate concrete
- 117 publications published over a period of 42 years from 1973 to 2014
- 476 concrete mixes analyzed
- Influence of recycled aggregates' quality on the modulus of elasticity of concrete
- E_{cm} - f_{cm} relationship of recycled aggregate concrete according to the EC2